Report To
Central Davis Sewer Improvement District
2627 W Shepard Lane
Kaysville, UT 84039
(801) 451-2190

Hydrogen Sulfide in Farmington Bay and the Great Salt Lake: A Potential Odor-Causing Agent

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Summary

Odors from Farmington Bay and/or the Great Salt Lake frequently impact residents of Salt Lake and Davis counties, but the agent causing the problem and the origin of the odor is uncertain. Hydrogen sulfide (H_2S) gas is produced in the deeper layers of water in Farmington Bay and Gilbert Bay in the Great Salt Lake, but these deeper waters are generally part of high salinity deep-brine layers that are resistant to wind mixing. Hydrogen sulfide has a "rotten-egg" odor and is a likely component contributing to the "lake stink." The goals of this study were to determine (1) whether wind driven mixing events drove mixing of the deep-brine layers in Farmington and Gilbert Bays, (2) determine the amount of hydrogen sulfide present in each of these bays, and (3) determine the potential of each area of the lake to release hydrogen sulfide from those deep-brine layers and cause odor events.

We found that in Farmington Bay, which was <1.5 m (5 ft) deep during the study, the deep-brine layer was entrained (mixed) four times in three months during high-wind events. By contrast, in Gilbert Bay, which has a deeper water column and more stable deep-brine layer, the brine layer was never completely entrained. However, the top 0.9 m (3 ft) of the deep brine layer eroded between July and October. Hydrogen sulfide concentrations in the surface mixed layers of both bays were insignificant on each sampling date, but concentrations in the deep-brine layers were significant. In Farmington Bay H_2S concentrations reached 8 mg/L in the deep-brine layer. In Gilbert Bay H_2S concentrations in the deep-brine layer ranged from 11 mg/L in late July to 4 mg/L in November 2003. The higher concentrations in Gilbert Bay are likely due to decreased mixing and therefore increased time intervals of hydrogen sulfide accumulation in Gilbert Bay. Both bays may release H_2S into the airshed, and thus contribute to odor problems. Large releases of H_2S into the water columns could result in rapid deoxygenation and toxicity to aquatic organisms. Detailed whole water column monitoring of oxygen, salinity, and H_2S concentrations in both bays should be undertaken to assess these potential threats. It will necessary to do these studies at a variety of lake levels in order to fully understand the driving mechanisms creating H_2S and allowing it to be released from the lake.

Introduction

The Great Salt Lake is a unique body of water, with very complicated hydrologic characteristics. It is the third largest and sixth saltiest hypersaline water body in the world. It also has very shallow mean and maximum depths, making it uncommonly shallow for its very large surface area. Because the lake is so shallow and has such a large fetch (length of lake on which the wind acts), the water column can be easily mixed by wind events. This characteristic, coupled with frequent high wind events in the Salt Lake Valley, lead to a polymictic mixing regime where the lake mixes many times a year. Most lakes stratify during the summer with warm water on the surface, and cooler, denser, water on the bottom. In deep lakes, this stratification is usually broken down only in the spring and fall, but in shallow lakes, winds may frequently mix the lake from top to bottom, making the water column *isothermal*, or the same temperature throughout. Other studies have found that the frequency, strength and duration of wind events effects currents, temperature, and nutrient cycling in polymictic lakes (MacIntyre 1993).

The mixing regime of the Great Salt Lake has been further complicated by the construction of several causeways in the lake (Figure 1). The Antelope Island and railroad causeways have artificially created three bays in the Great Salt Lake: Farmington Bay, Gilbert Bay and Gunnison Bay (Figure 1). These causeways allow dense, high salinity water to underflow from more saline bays into less saline bays, creating salt wedges or deep-brine layers (Figure 2). The density differences between the saltier deep-brine layer and the less salty overlying water is much greater than density differences due to temperature, and mixing to the bottom of a deep-brine layer requires huge amounts of energy input from the wind. In many lakes, these deep-brine layers seldom, if ever, mix. Deep-brine layers are commonly found in both Gilbert and Farmington Bay. With salt-induced stability of the bottom water, temperatures in the surface layer can fluctuate relatively independently of the deep-brine layer. The water layer above the deep-brine layer may undergo daily and weekly fluctuations in temperature, but the deeper layer is protected from solar radiation and therefore fluctuates much less. During cold periods, the surface water can become colder than the deep-brine layer, and during warming events, the surface water warms much more than the underlying water. In the transition from a warm period to a cold period, the water column can even become isothermal without the lake mixing through the deep-brine layer. Although deep-brine layers may mix infrequently, it is possible that the top of a deep-brine layer is frequently "shaved" off by wind events while the layer is replenished with water from higher salinity areas.

The deep-brine layers in Farmington and Gilbert Bays can have a huge effect on chemical reactions that occur in the deep water of these bays, because they can exacerbate anoxia (absence of oxygen). Bacterial respiration of organic matter that accumulates in the sediments and deep brine layers can remove oxygen from that stratum. A dominant source of organic matter is sedimenting plankton from the upper strata where photosynthesis occurs, but riverine inputs and accumulated organic matter will also contribute to the deoxygenating. Bacterial respiration can deplete the oxygen in these deep-brine layers relatively quickly, and since these water layers are resistant to mixing, anoxia can be maintained for long periods of time. Anoxic conditions lead to distinctly different chemical reactions that do not occur when oxygen is present in water. The stable deep-brine layers also keep oxygen-rich water from reaching the sediments where bacterial decomposition rates are even higher. If anoxia develops in a deep-brine layer, oxygen can be replenished by three mechanisms. First, complete mixing of the water column by very high winds can distribute oxygen throughout the water column and homogenize salt concentrations. A new layer of high-salinity water could then intrude, and this water would likely be oxygenated. Secondly, if the overlying water column is clear enough, light may penetrate into a deep-brine layer and allow oxygen-producing photosynthesis to occur. Finally, if there are internal waves, called seiches, that slosh between Gilbert and Farmington Bays, some oxygenated water might intrude locally into the deep brine layer.

Anoxic conditions, particularly in the sediments, allow the abundant sulfates in the lake to be reduced to hydrogen sulfide gas (H_2S). This gas possesses an odor similar to rotten eggs and is likely an important source of the odor problems plaguing Salt Lake City (Israelsen et al. 1985). Hydrogen sulfide has been linked to odor problems in cities located near eutrophic estuaries and other bodies of saline water (e.g. Muezzinoglu 2000). It is not clear what parts of the Great Salt Lake contribute to these odors. Factors controlling the rate of hydrogen sulfide production include the concentration and availability of organic matter, the concentration of sulfates available to be reduced, and temperature (Effler et al. 1988). The conditions in Farmington Bay are highly favorable for hydrogen sulfide production; eutrophication in the bay provides a large source of highly decomposable organic matter, sulfates are abundant in the hypersaline water, and water temperatures can be very high in the shallow waters of the Great Salt Lake. Even under natural conditions, saline lakes and estuaries produce hydrogen sulfide in the sediments, and the early Great Salt Lake explorer, John Fremont noted strong odors when they drug their boats through soft sediments of the Bear River wetlands in 1843. Warning signs of growing odor problems in Farmington Bay appeared as early as the 1970's. Coburn and Eckhoff (1972)

warned that if anoxic conditions developed in the bay, odor problems might ensue. Additional warnings of severe eutrophication were available from projections of the water quality in a proposed freshwater impoundment (Lake Wasatch) on the east side of the lake (Chadwick et al. 1986; Sorensen et al. 1988). However, a thorough study of H_2S abundance in the bay has never been conducted.

Some preliminary examinations have indicated that hydrogen sulfide concentrations are already high in Farmington Bay and the Great Salt Lake, and thus deserve further study. Results from a USU student project in a 2002 practicum class indicated that H_2S concentrations were >12 mg/L in the deeper areas of Farmington Bay within a deep-brine layer, but that concentrations were low in shallower areas where the brine layer was absent (Marcarelli et al. 2003). H_2S concentrations were >100 mg/L within the surficial sediments of the deep-brine layer. Anoxia and hydrogen sulfide also occurs in the deep-brine layer of Gilbert Bay (Wurtsbaugh and Berry 1990). Brandt et al. (2001) measured rates of sulfate reduction to H_2S in the surface sediments of Gilbert Bay that were among the highest ever reported for natural environments. Additionally, when incubated in laboratory experiments, they found that maximum sulfate reduction rates in Gilbert Bay sediments occurred between salinities of 3–9%, indicating that the salinity in Gilbert Bay is actually above the concentration where maximum reduction occurs, and therefore even higher rates of fixation are possible in less saline parts of the Great Salt Lake, such as Farmington Bay (Brandt et al. 2001).

Hydrogen sulfide can have negative effects on aquatic organisms. Sulfide is directly lethal to many organisms in the range of 1-5 mg/L (Watts et al. 2001). Hydrogen sulfide is highly soluble, so it diffuses out of the sediments and into the water column easily when a layer of anoxic water overlies sediments. Ingvorsen et al. (1981) found that hydrogen sulfide production was primarily localized in the surface sediments of Lake Mendota; only 18% of the total sulfide production took place in the water column of the lake's anoxic bottom water (hypolimnion). When anoxic water comes in contact with oxygen, hydrogen sulfide is oxidized to sulfate rapidly, and oxidation requires two molecules of oxygen for every molecule of sulfide (Effler et al. 1988). This high demand for oxygen can lead to anoxia in the water column of lakes for days after a mixing event occurs. Hydrogen sulfide production and subsequent mixing has been linked to anoxic events in a freshwater lake (Effler et al. 1988) and the Salton Sea (Watts et al. 2001). In the Salton Sea, Watts et al. (2001) linked the combined effects of hydrogen sulfide toxicity and anoxia caused by hydrogen sulfide oxidation to mass die-offs of phytoplankton, zooplankton,

and fish. Oxygen recording equipment placed in Farmington Bay in October 2001 indicated that during the day the water was supersaturated with oxygen, but overnight the mixed water column became anoxic despite strong winds that should have aerated the water column (Wurtsbaugh and Marcarelli 2002). This anoxia could have been the result of bacterial respiratory demand from the water column and sediments, or because H_2S was mixed into the water column, thus creating additional chemical oxygen demand.

The objective of our study was twofold. First, we wished to examine the stability of the deep-brine layer in Farmington Bay and Gilbert Bay and determine if we could identify mixing events in these two water bodies. Secondly, we wished to measure hydrogen sulfide concentrations in Farmington and Gilbert Bays, with particular attention to concentrations within the deep-brine layers. We hypothesized that much of the odor coming from the lake originates in these layers, and that hydrogen sulfide is released during wind mixing events that "shave" off a portion of one or more of the brine layers, thus leading to mixing into the upper water layer and the overlying air. By analyzing how frequently mixing occurs and how much hydrogen sulfide accumulates in the two different bays, we hoped to determine whether the two bays contributed differently to odor events.

Methods

Mixing Regime:

Since the deep-brine layer and surface waters usually have different water temperatures, we attempted to monitor the presence and mixing of deep-brine layers using temperature loggers, or thermistors. A more ideal analysis of mixing in these deep-brine areas would use conductivity sensors to monitor mixing events. However, long-term conductivity loggers are expensive and impractical for this kind of exercise at this time. The inability to distinguish deep-brine mixing events from isothermal conditions, as described in the introduction, is one disadvantage of using thermistors as a surrogate for measuring mixing in salt-stratified lakes. Nevertheless, a careful examination of the thermistor data usually allows one to distinguish simple isothermal conditions from true mixing events.

Thermistor strings were deployed in Farmington Bay and in Gilbert Bay to continuously record temperatures every 10 minutes. Hobo Water Temp Pro thermistors were used (Onset Computer Co.). In Farmington Bay thermistors were deployed at 25-cm intervals at station P1A, which was located near the southern extent of the deep brine layer and was initially 1.5-m (5 ft)

deep (N 41° 02.985' W 112° 11.321'; Figure 1). This site is near the principal water sampling station of Davis County and the Utah Department of Water Quality. This string collected data for June and July 2003; however, the chain was lost at some point following 31 July and data after this point was not recovered. Another string was deployed at an offshore site in Gilbert Bay (N 41° 06.63' W 112° 27.034'; 1018 Buoy, Figure 1) at the end of July and recorded temperature through the beginning of November 2003. Thermistors on this chain were located 0.5-m below the surface, and at 0.0, 0.7, 1.2, 1.5, 1.8, 2.1, 2.4, 2.7, 3.0 and 3.7-m above the bottom in the region of the deep brine layer.

To determine whether wind-driven mixing events could be linked to deep-brine layer mixing, weather data, including wind speed, wind direction and air temperature collected at the Salt Lake City International Airport were obtained from Mesowest (Station SLC, http://www.met.utah.edu/mesowest/). These parameters are recorded at 1-hr intervals. We analyzed this data at one hour and daily intervals to compare with temperature data in the lake and determine if mixing events could be delineated.

Hydrogen sulfide sampling:

Hydrogen sulfide was measured in Farmington Bay on five dates in 2003 (15 May, 6 Jun, 28 Aug, 23 Oct and 12 Dec). Samples on the first four dates were collected at two or three depths near the southern extent of the deep-brine layer at Station P1A. On 23 Oct, samples were collected at dawn (7:30 AM) and after sunlight had been on the water for 3.5 hr (11:00 AM) to examine temporal variations in oxygen and hydrogen sulfide concentrations. Because 2003 was a major drought year, water depths in Farmington Bay declined from 1.5-m in May to 0.75-m in October. In October the deep brine layer at station P1A was negligible. Consequently, on 12 Dec we measured profiles of hydrogen sulfide at a station closer to the Antelope Island causeway (N 41° 03.458' W 112° 12.812'; Station H_2S, Figure 1) where the water was deeper and the deep-brine layer was thicker. Duplicate or triplicate samples from each depth were collected with an 8-L horizontal Van Dorn bottle; bottles were filled using the "overflowing bottle" procedure that insures that oxygen does not enter the bottle and change redox conditions. Samples were preserved using zinc acetate and the amount of hydrogen sulfide present was determined with the iodometric titration method (APHA 2000) within 48 hours. The limit of detection for the method was 0.31 mg/L.

Hydrogen sulfide was also sampled on three dates in 2003 at the offshore site in Gilbert Bay where the thermistor chain was located (29 July, 4 Sept and 10 Nov). Duplicate samples were collected at the top and bottom of the mixed layer and at three depths within the deep brine layer. Hydrogen sulfide concentrations were measured as above.

On each sampling date, profiles of dissolved oxygen and temperature were taken at each study site with a YSI model 58 DO/temperature meter. Oxygen measurements were corrected for temperature and salinity (SENSOREX 2004). On several dates in both Farmington Bay and Gilbert Bay, the YSI measurements were calibrated against Winkler dissolved oxygen titrations (Azide modification; APHA 2000). Samples for Winkler titrations were collected with an 8-L horizontal Van Dorn bottle and the overflowing bottle procedure. Salinity profiles were measured with a refractometer.

Results and Discussion

Mixing Regime:

To examine how often mixing events release the hydrogen sulfide stored in the deep brine layers of both Farmington and Gilbert Bays, we examined the long-term temperature records obtained using the thermistor chains (Appendix 1). A dominant pattern in the temperature records is a strong daily (24 h) temperature cycle in the surface waters, but a weak or non-existent cycle in the bottom layers. In Farmington Bay, the daytime heating and nighttime cooling frequently caused temperature shifts of 6-8°C (11-14°F), whereas in Gilbert Bay the heating was attenuated over a deeper water column so that daily fluctuations reached only about 2°C. In addition to the daily cycles, the thermistors in Gilbert Bay recorded other temperature cycles in the deep-water layer, likely caused by internal waves that periodically moved water from deeper areas of the bay to the site where our sensors were deployed.

It is evident from the temperature record that Farmington Bay mixed to the bottom relatively frequently, while the entire water column in Gilbert Bay seldom, if ever, mixed completely (Figures 3 and 4). The temperature record indicated that mixing events in Farmington Bay occurred irregularly and were associated with high wind events. For example, high daily mean and maximum wind speeds on 10 June and 13 June were associated with periods where the daily temperature patterns in Farmington Bay were disturbed and the temperature lines converged, indicating that mixing likely occurred (Figure 3a). Similar events were observed on

22 June and 30 June (Figure 3b, c). Taken together, this indicates that Farmington Bay may have mixed to the bottom four or more times during our 2-month sampling window.

In contrast, the temperature record for Gilbert Bay indicates that mixing to the bottom never occurred from late July to mid-November, despite the occurrence of several high wind events (Figure 4 b, c). The water column did become isothermal around 10-11 October (Figure 4 b, c). However, water column stability caused by the presence of the deep brine layer likely prevented mixing to the bottom. The interpretation that the deep-brine layer was not disturbed is supported by the fact that the surface layer continued to cool in October; temperatures in the bottom of the bay remained relatively stable, and soon were warmer than the surface layer, indicating that these two layers remained independent of one another even after isothermal conditions occurred.

Despite the lack of mixing of the deep brine layer in Gilbert Bay, the temperature record indicates that from late July to November the deep brine layer was eroded. This can be seen in Figure 4 b, c. Note that in August temperatures at 1.5-m (5 ft) above the bottom (blue line) were independent of the surface temperatures. However, a sustained wind around October 10th appeared to have mixed the water column into that layer. Subsequently, nighttime temperatures were usually isothermal to at least 1.5-m above the bottom. This erosion of the deep brine layer is also shown in Figure 5. In late July and early August, the lake was mixing at night to an elevation of about 4175.5 feet, with a deep brine layer about 6.5-ft (2-m) thick. As the lake elevation decreased by evaporative loss, the thickness of the mixed layer was maintained or grew slightly, thus eroding the top of the deep brine layer. By late October the lake was mixing to an elevation of 4172.5 ft, leaving a brine layer 3.5-ft (1.1-m) thick.

Hydrogen Sulfide Concentrations:

Concentrations of hydrogen sulfide in the surface mixed layers were always at, or below our level of detection, but significant concentrations were found in the deep brine layers of both Farmington Bay and Gilbert Bay on all sampling dates (Figures 6 and 7; Appendix III). Concentrations in the lower depths of Farmington Bay (near the southern extent of the deep-brine layer) ranged from 1 to 3.9 mg/L. These concentrations are low compared to previously measured concentrations (25 mg/L; Marcarelli et al. 2003), but similar to those measured in the anoxic layer of the Salton Sea (ca. 5 mg/L; Watts et al. 2001) and to those measured in eutrophic Onondaga Lake (Effler et al. 1988). On each date that hydrogen sulfide levels were

detectable in the hypolimnion, oxygen concentrations measured in the hypolimnion with both the YSI meter and the Winkler method were zero or near zero. The one occasion when low levels of hydrogen sulfide were measured in the lower layer of Farmington Bay was on the day we sampled at both 7:30 AM and 11:00 AM (23 Oct). At 7:30 AM, the bottom layer of Farmington Bay was anoxic and the sulfide concentration measured was 1.64 mg/L. By 11 AM, oxygen in the lower layer had risen to 1.75 mg/L, and sulfide concentration was only 0.26 mg/L (Figure 6). Salinity profiles at these two times (Appendix III) indicated that the deep-brine layer had largely disappeared in the intervening 3.5 hours, possibly as the result of internal wave action. On 12 December, when the samples were taken in deeper water closer to the Antelope Island causeway, the hydrogen sulfide concentration in the deep-brine layer was 8.4 mg/L, higher than had been measured at the other location in Farmington Bay. This indicates that hydrogen sulfide production may be highest in the area of Farmington Bay underlain by the deep-brine layer, a conclusion also reached by a student project in 2002 (Marcarelli et al. 2003).

In both the Salton Sea and Onondaga Lake, concentrations of hydrogen sulfide similar to those found in Farmington Bay were sufficient to cause anoxia in the entire water column following either wind-driven mixing events or fall turnover events. For a few months in the summer of 2003, we had surface and deep oxygen sensors deployed near station P1A in Farmington Bay as part of a larger project we are conducting at Farmington Bay. These recorded oxygen concentrations at 20-minute intervals. Interestingly, these sensors captured a 60-hr anoxia event in Farmington Bay (Figure 8a), starting near 10:00 PM on 25 July 03 and lasting until noon on 28 July 03. The initiation of this anoxic event was closely aligned with a high wind event on the night of 25 July (Figure 8b). One hypothesis to explain this anoxic event could be that the wind event caused the water column in Farmington Bay to mix completely, resulting in the degradation of the deep-brine layer and the release of hydrogen sulfide. Wind mixing could also suspend sediments, which may release more hydrogen sulfide. A surface salinity sensor on the buoy indicated that higher salinity water had been mixed into the surface water. The subsequent oxidation of hydrogen sulfide released by the mixing of the deep-brine layer could have been responsible for the prolonged oxygen depletion observed in Farmington Bay on those dates. Note that in most lakes high winds would aerate and oxygenate the water column; the opposite effect was observed here.

In Gilbert Bay, hydrogen sulfide concentrations were consistently high in the deep-brine layer, ranging from 3.9 mg/L in November to 11.0 mg/L in July (Figure 7). The deep-brine layer was

consistently anoxic and on the three sampling dates the top of the deep-brine layer ranged from 6 to 7-m (17.7-23.0 ft) deep. However, hydrogen sulfide extended higher in the water column on 29 July and 4 Sept than on 10 Nov, and concentrations were lower on 10 November as well. It is possible that a wind-mixing event sometime between these two sampling dates may have shaved off part of the deep-brine layer, releasing the hydrogen sulfide stored in that water. This is consistent with the decreasing depth of the deep-brine layer shown in Figure 5. Alternately, the shift in the uppermost extent of hydrogen sulfide could have been caused by a large internal wave that could result in changes in the upper extent of the deep-brine layer over the course of one to ten days. Unfortunately, either explanation cannot be supported or refuted by our temperature logger data, which ended on 30 Oct. Overall, hydrogen sulfide concentrations in Gilbert Bay are comparable to the concentrations measured in the deep-brine layer of Farmington Bay, and indicate that hydrogen sulfide production in Gilbert Bay could contribute to odor events.

Conclusions

The objective of this study was to examine hydrogen sulfide production in Farmington Bay and Gilbert Bay and assess the potential of these two parts of the Great Salt Lake to contribute to the odor events observed by residents of Salt Lake and Davis counties. Our sampling indicates that significant amounts of hydrogen sulfide are produced in both parts of the Great Salt Lake, and both water bodies may mix to, or near, the bottom and release hydrogen sulfide from deep-brine layers. Farmington Bay may turn over and release H_2S frequently. The lower concentrations of hydrogen sulfide observed in Farmington Bay may be due to frequent water column turnover, which would lead to shortened periods of hydrogen sulfide production and accumulation in the deep-brine layer. In contrast, concentrations of hydrogen sulfide in the deep-brine layer of Gilbert Bay were higher than those found in Farmington Bay, but may have had some time to accumulate due to infrequent mixing. Because Farmington Bay has much higher organic loads (algal concentrations) than Gilbert Bay (Gliwicz et al. 1995; W. Wurtsbaugh, unpublished data) this explanation is reasonable. Additionally, Brandt et al. (2001) found that the lower salinity characteristic of Farmington Bay could produce higher sulfate reduction than the hypersaline water in Gilbert Bay. However, examination of the sediments in Farmington Bay has shown that organic matter content in the sediments is much lower in areas of Farmington Bay not overlain by the salt wedge (Marcarelli and Wurtsbaugh 2003). This may result of lower amounts of hydrogen sulfide produced in the sediments of Farmington Bay (when considered over the entire bay) compared to the very high rates that have been measured in the

sediments of Gilbert Bay (Brandt et al. 2001). This could be very important since it has been observed in other lakes that most of the hydrogen sulfide contained in the deep brine layer is produced in the sediments and released into the overlying anoxic water (Ingvorsen et al. 1981). More extensive research will be necessary to determine why hydrogen sulfide concentrations in Farmington Bay differed from those Gilbert Bay.

Since hydrogen sulfide concentrations are higher, when Gilbert Bay is mixed it could cause odor events comparable to those caused by Farmington Bay. Also, shaving of the deep-brine layer may lead to more frequent, but lower magnitude, releases of hydrogen sulfide from Gilbert Bay. Additionally, the thick overlying mixed layer in Gilbert Bay contains considerable oxygen, and thus could oxidize H_2S before it reaches the surface. An additional source of H_2S is the mud flats of Farmington Bay and other regions of the Great Salt Lake. Decomposition of organic matter in these sediments likely drives H_2S production, and since these flats are extensive, they have a large potential to contribute odors. For example, intense odors are frequently noted along the portion of the Antelope Island causeway that is surrounded by damp mud flats.

The magnitude of release from each of the bays will also be dependent on the aerial extent of the deep-brine layers. The hypsographic curve (area vs. depth) for Farmington Bay indicates that the deep-brine layer underlay an area of approximately 15-20 km^2 during the summer of 2003. In contrast, the deep-brine layer in Gilbert Bay likely covered 630-750 km^2 (Cruff 1986). Both bays thus hold appreciable H_2S, but the greater stability of the water column in Gilbert Bay likely causes slow releases of this odor-causing and toxic gas. The aerial coverage by the deep-brine layers likely changes markedly with changes in water surface elevations in each of the lake's major bays.

Further work is needed to assess the importance of hydrogen sulfide in relation to odor events and the effects on the biota. In particular, research is needed when water levels are higher in the lake, because this will influence not only the areal extent of the deep-brine layers, but also their thickness and stability. The potential impact of mixing events in Gilbert and Farmington Bays on the biota of the Great Salt Lake should also be examined under a variety of conditions. Turnover events may release large amounts of hydrogen sulfide produced in the deep-brine layer, which is then oxidized to sulfate and consumes oxygen in the water column. In the Salton Sea, turnover events that released hydrogen sulfide stored in the anoxic hypolimnion lead to as much as four days of anoxia while sulfide was oxidized (Watts et al. 2001). Sulfide toxicity,

paired with anoxia, could have profound effects on brine shrimp and brine fly populations that have economic and ecological importance for the Great Salt Lake ecosystem.

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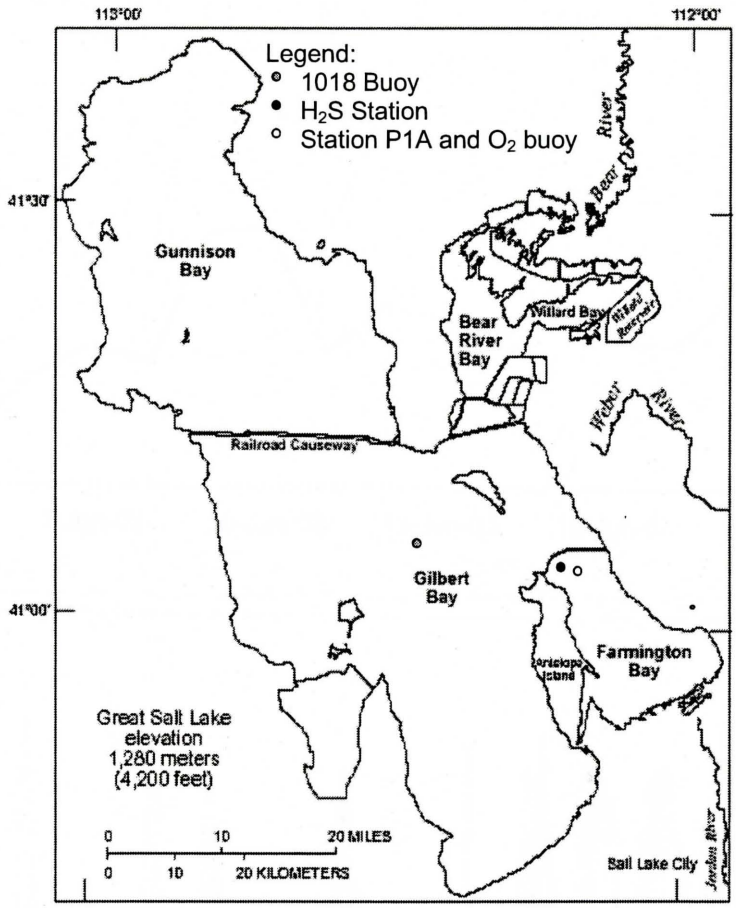


Figure 1: Map of Great Salt Lake, showing the locations of the Farmington Bay and railroad causeways and the sampling stations used in this study.

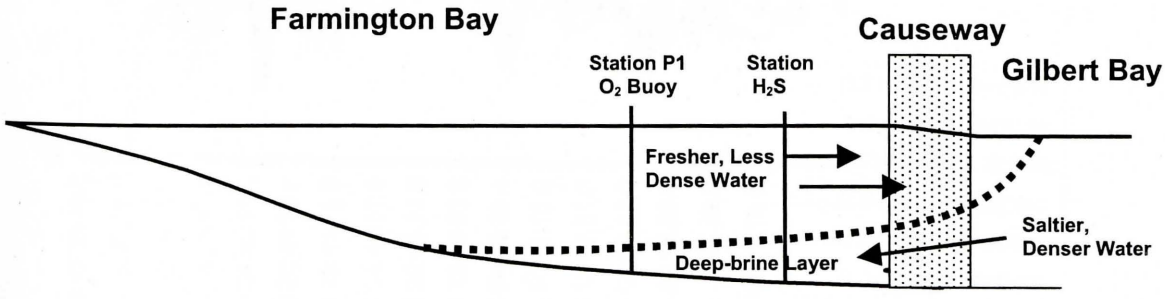


Figure 2: Formation of a deep-brine layer in Farmington Bay.

(a)

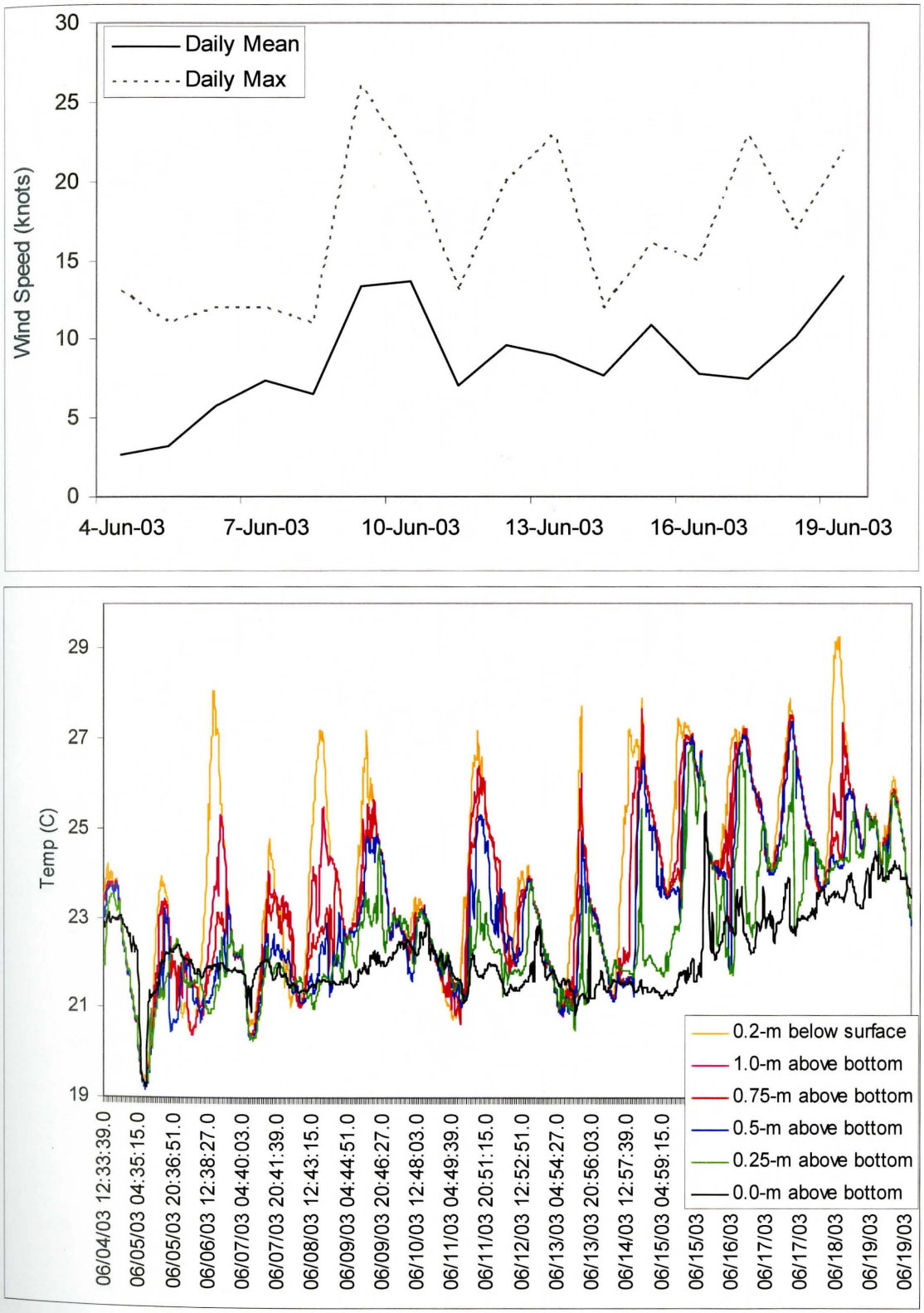


Figure 3(a): Matched temperature and wind data from Farmington Bay for 4-19 June 2003. Temperature data was obtained using a thermistor chain deployed in Farmington Bay, wind data was obtained from a weather station at the Salt Lake International Airport. Isothermal events are indicated when the colored lines approach each other. Note the high daily mean and maximum wind values and associated isothermal conditions on 10 and 13 June.

(b)

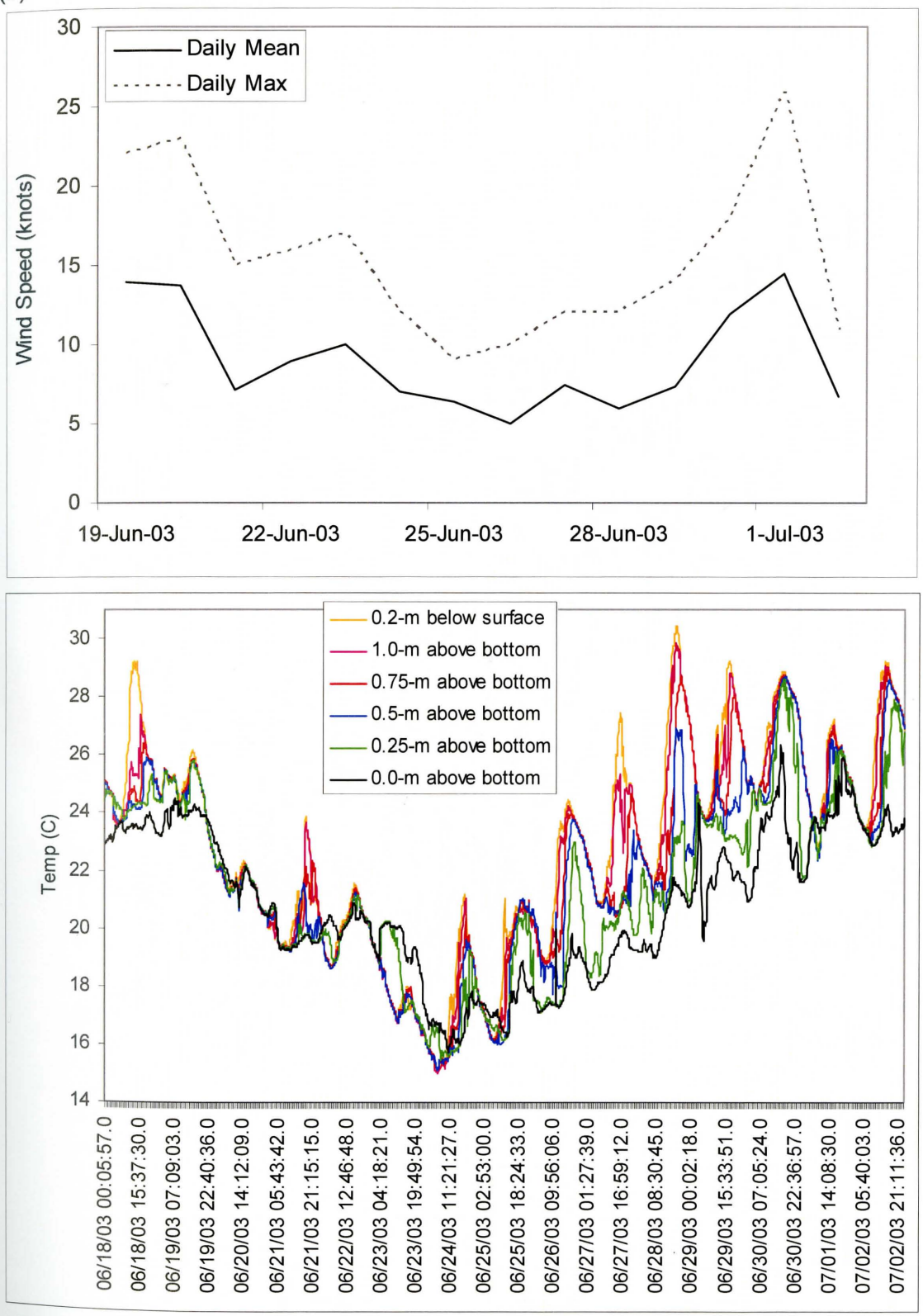


Figure 3(b) Farmington Bay: 19 June – 2 July 2003, note high daily mean and max wind values and associated isothermal conditions on 22 and 30 June.

(c)

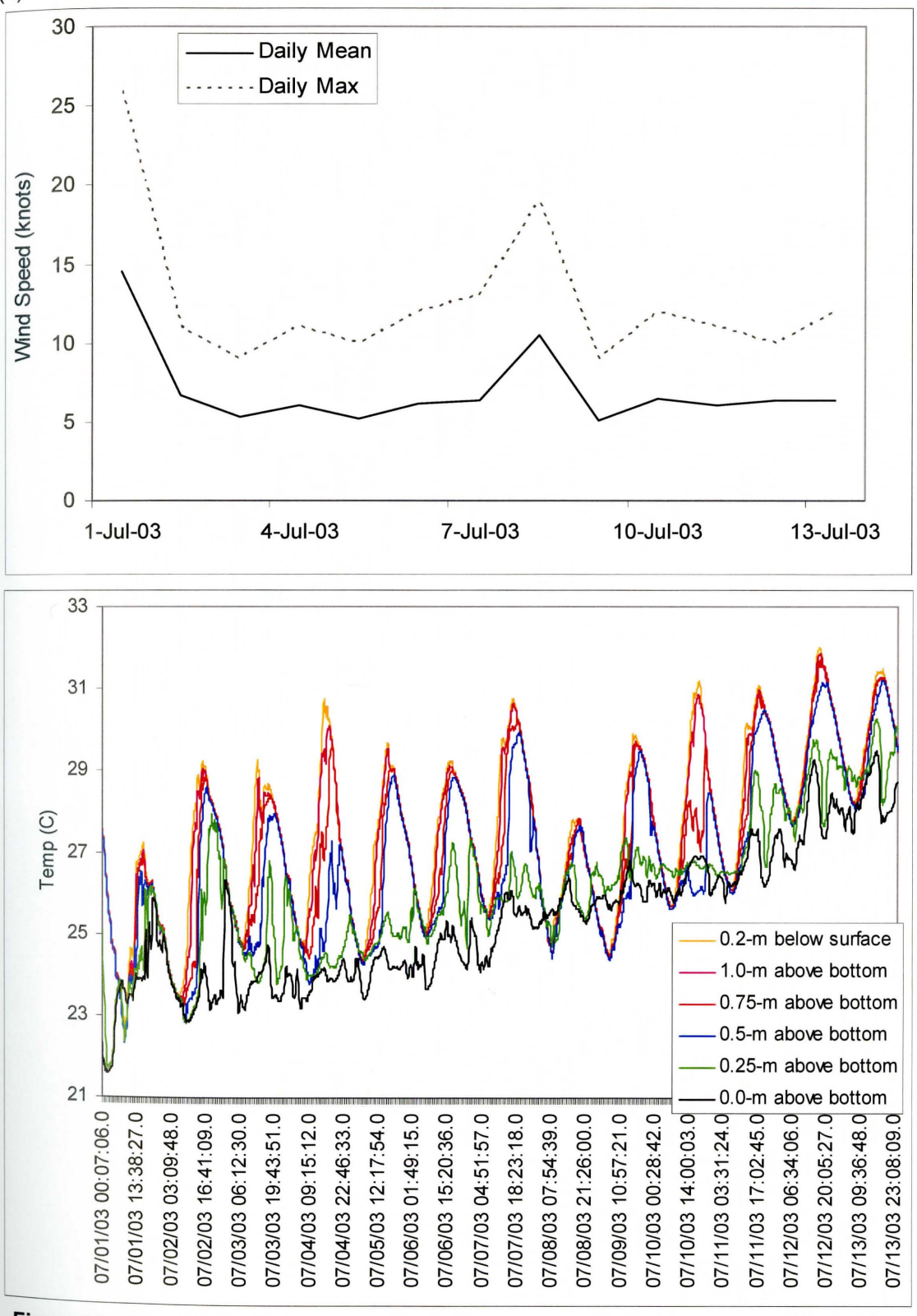
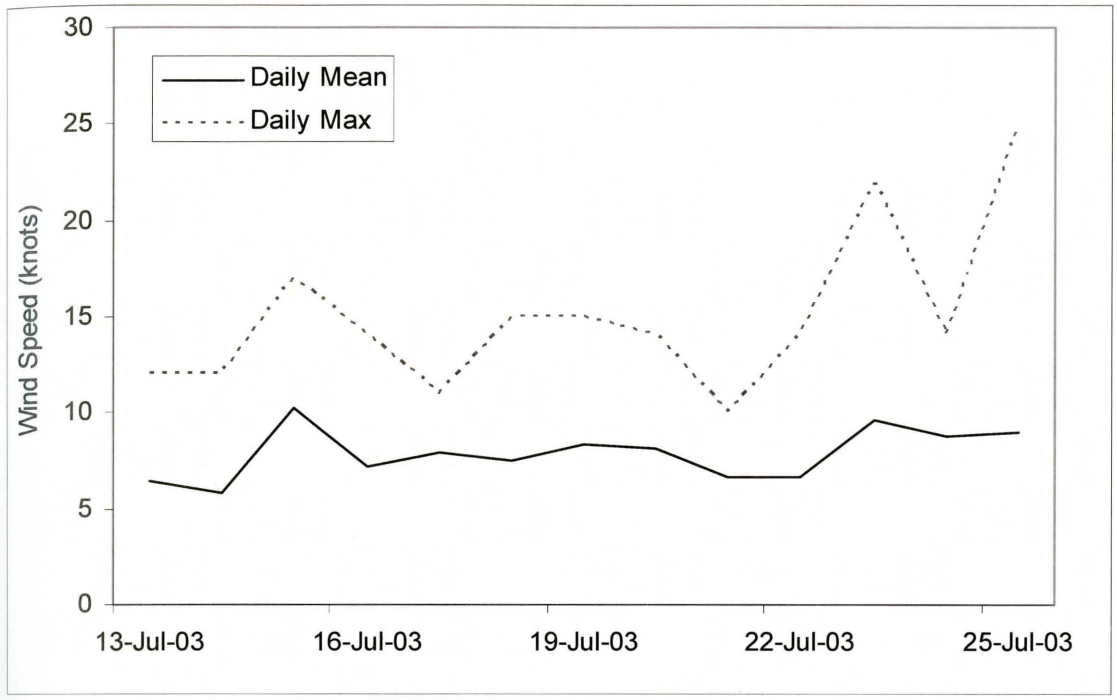


Figure 3(c) Farmington Bay: 1–13 July 2003, note regular daily temperature fluctuations and lack of isothermal conditions during this period.

(d)



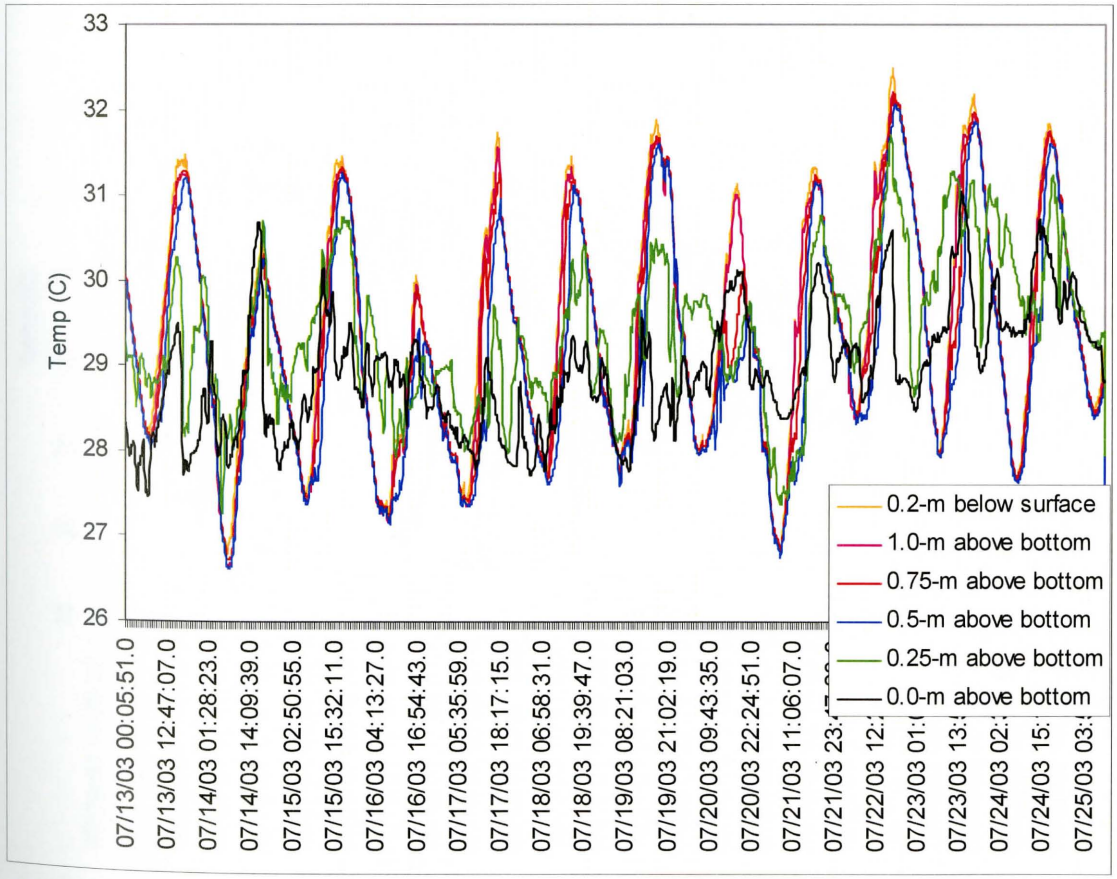
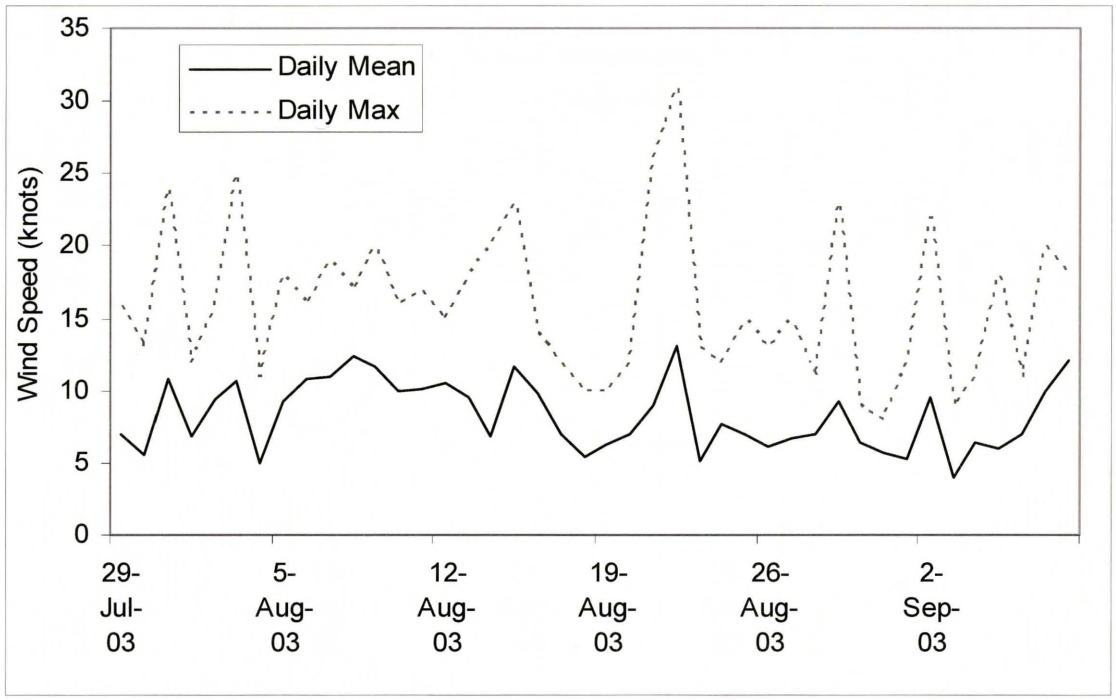


Figure 3 (d) Farmington Bay: 13–25 July 2003 (end of record). Note the regular daily temperature fluctuations and lack of isothermal conditions during this period.

(a)



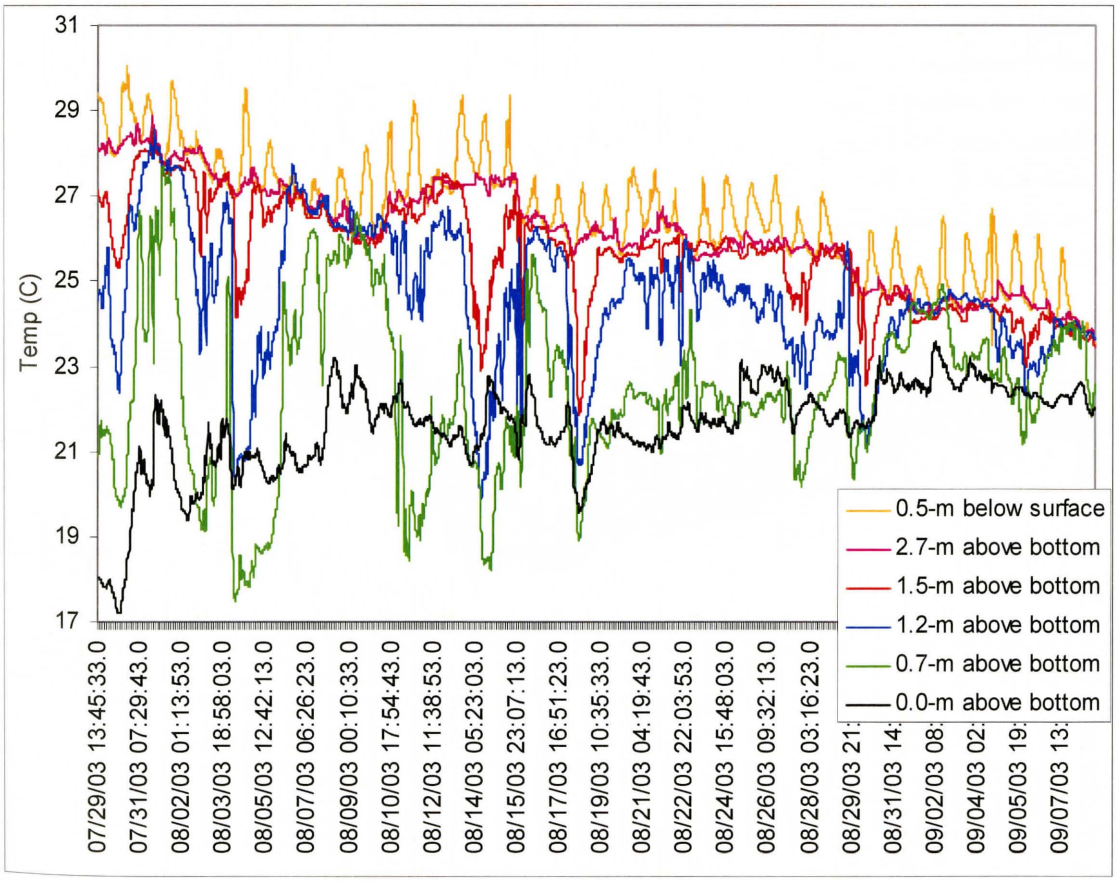
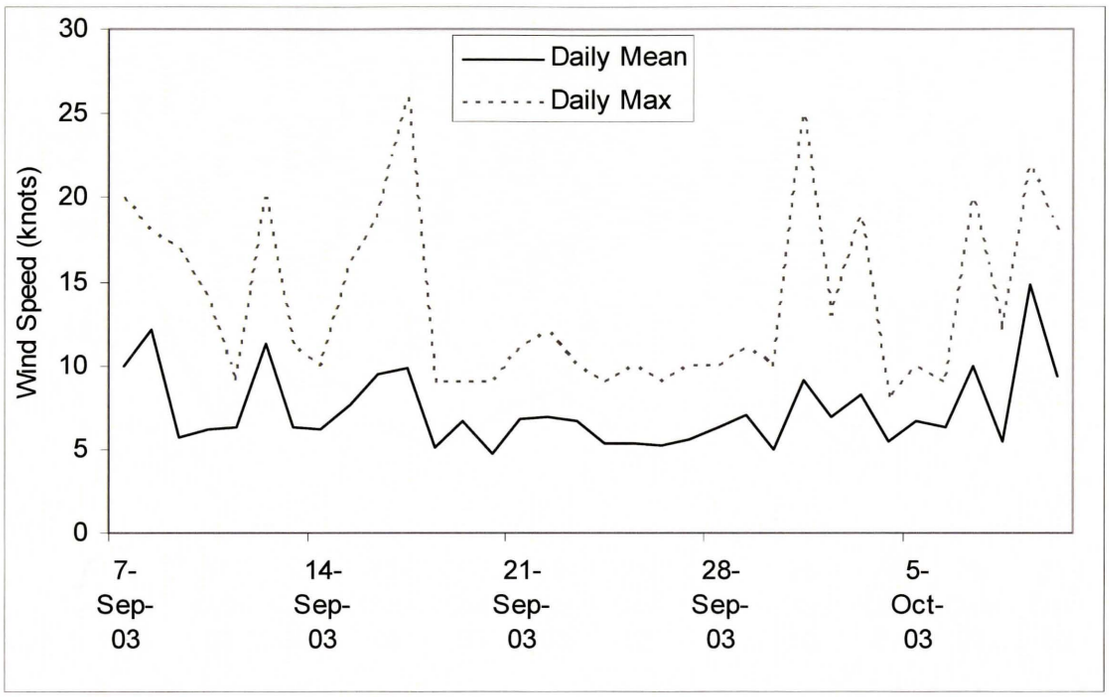


Figure 4(a): Matched temperature and wind data from Gilbert Bay from 29 July – 8 September 2003. Temperature data was obtained using a thermistor chain deployed in Gilbert Bay, wind data was obtained from a weather station at the Salt Lake International Airport. Graphs are separated by dates to allow careful examination of isothermal events, which are indicated where the colored lines approach each other. Note the lack of whole water isothermal conditions on any date, despite several high wind events.

(b)



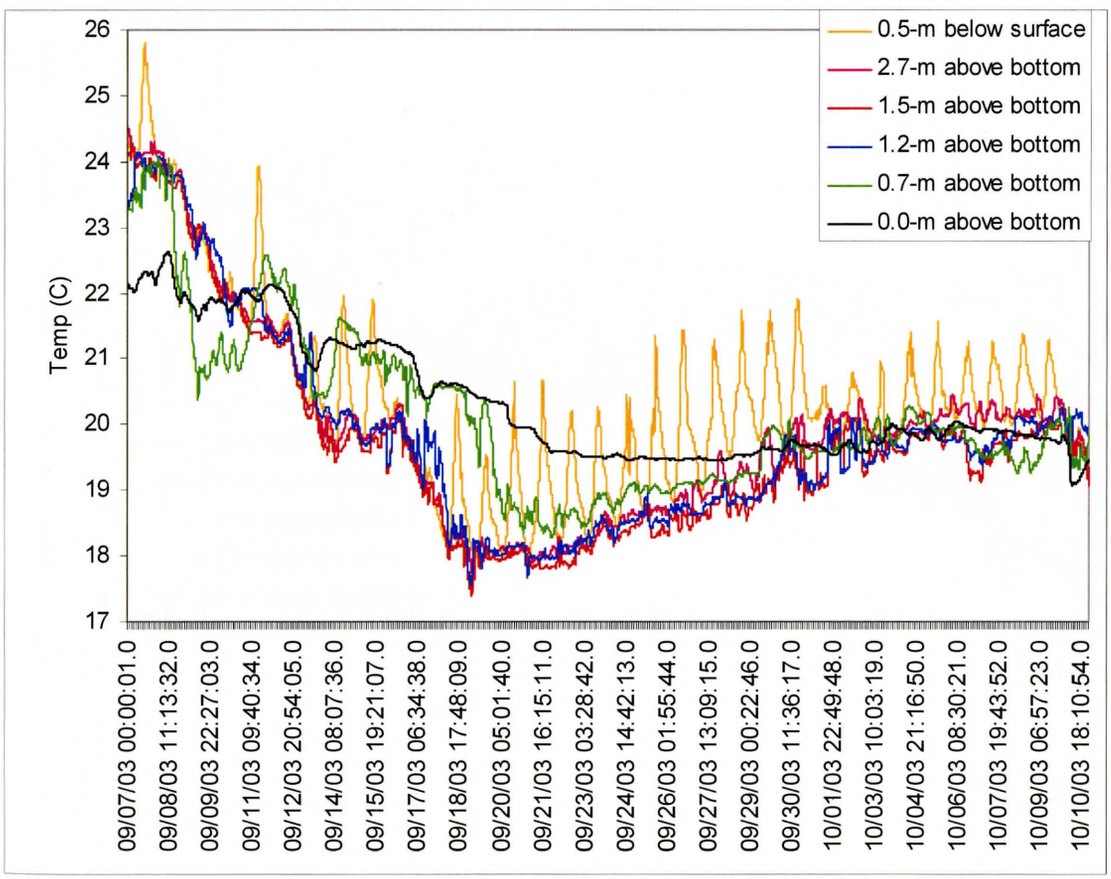


Figure 4(b): Gilbert Bay, 7 Sept – 10 Oct 2003, note initiation of isothermal conditions near the end of the record.

(c)

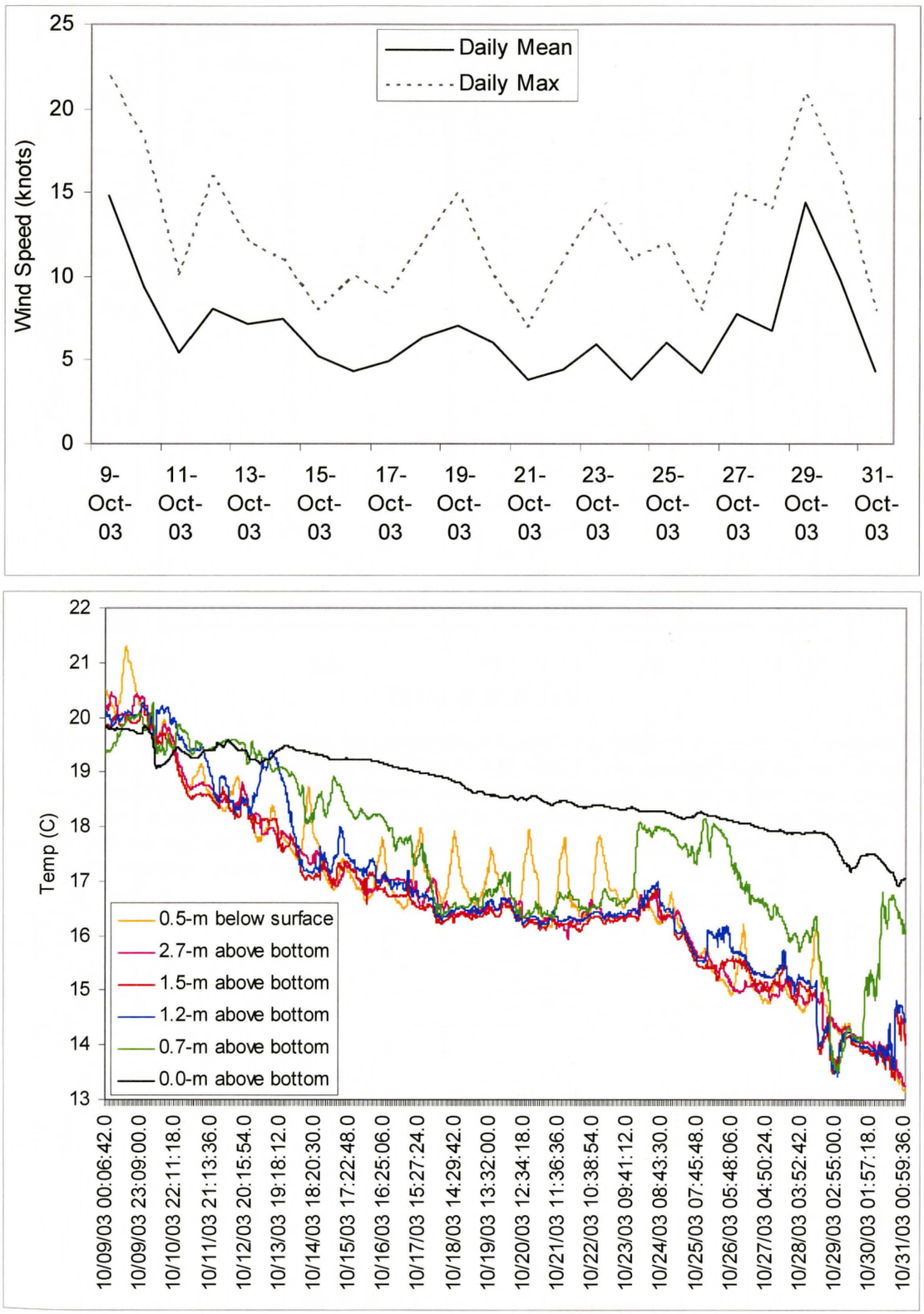


Figure 4(c): Gilbert Bay, 9 – 31 Oct 2003 (end of record). Note isothermal conditions on 10-11 October, with subsequent cooling of the surface layers and relative temperature stability of the deep-brine layer.

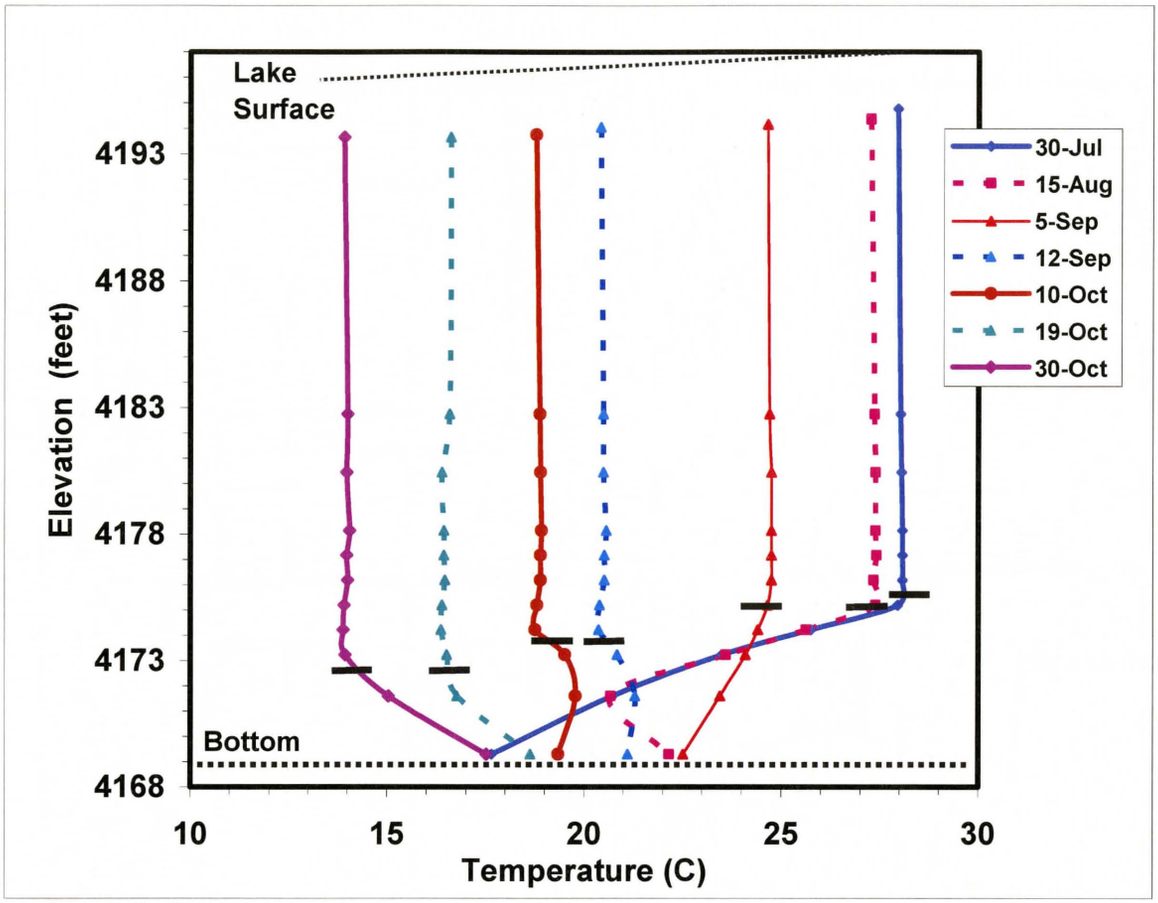


Figure 5: Temperature profiles on seven dates based on TempPro thermistors deployed at 11 depths. These profiles are from 4:00-5:30 AM, when solar radiation has not yet heated the surface layers. The black horizontal bars indicate the depth to which the water column was mixing each night, that is, the strata above the deep-brine layer. Note that from late July until the end of October, that the deep-brine layer eroded approximately 1.5 ft (0.46 m). Surface elevation of the lake declined 1.1 ft during this period.

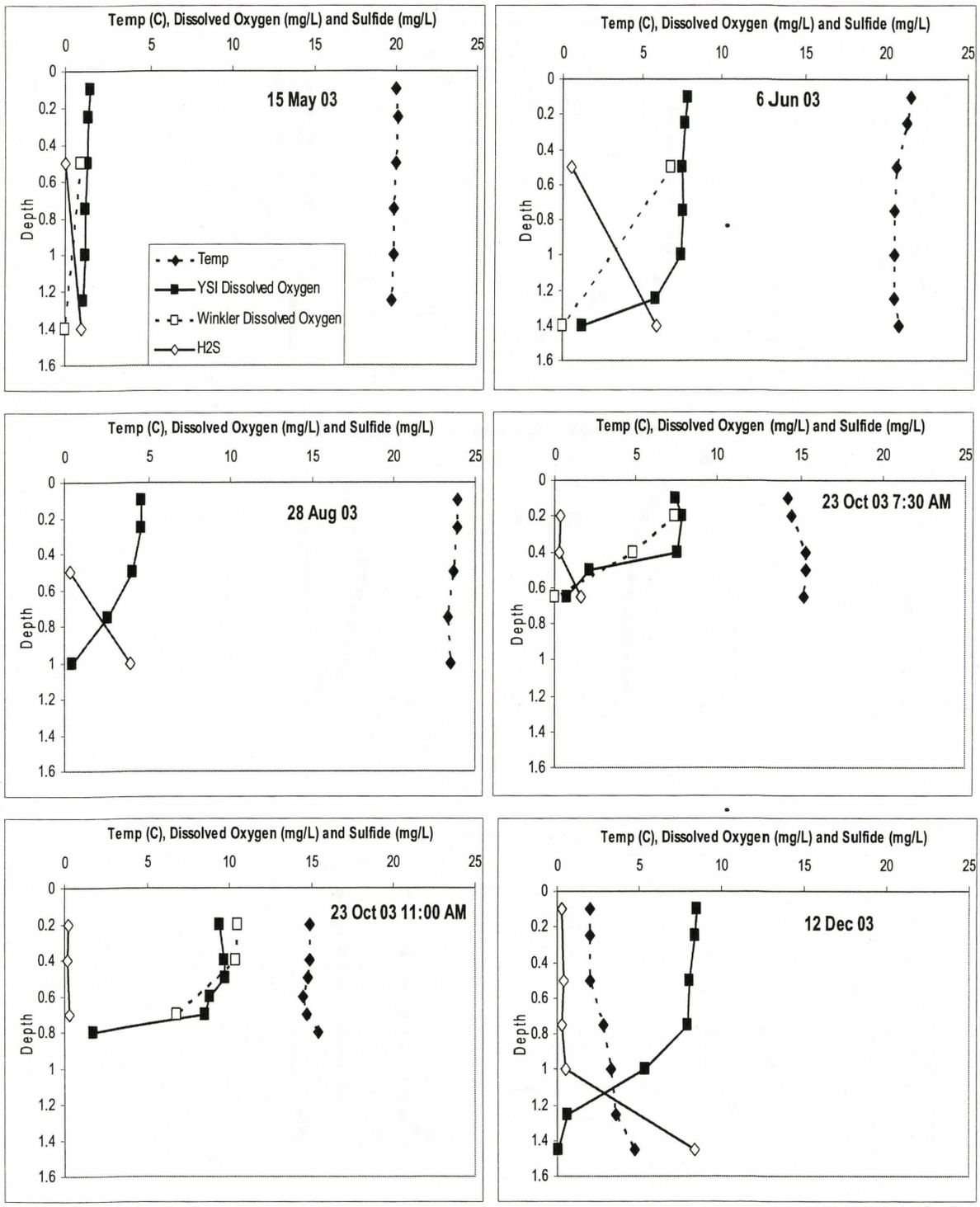


Figure 6: H_2S (total $S^=$), temperature, corrected YSI DO, and where available, Winkler DO profiles collected in Farmington Bay. Data from 15-May to 23-October were collected at station P1A, while the data for 12 December were collected at the H_2S station where the water was deeper.

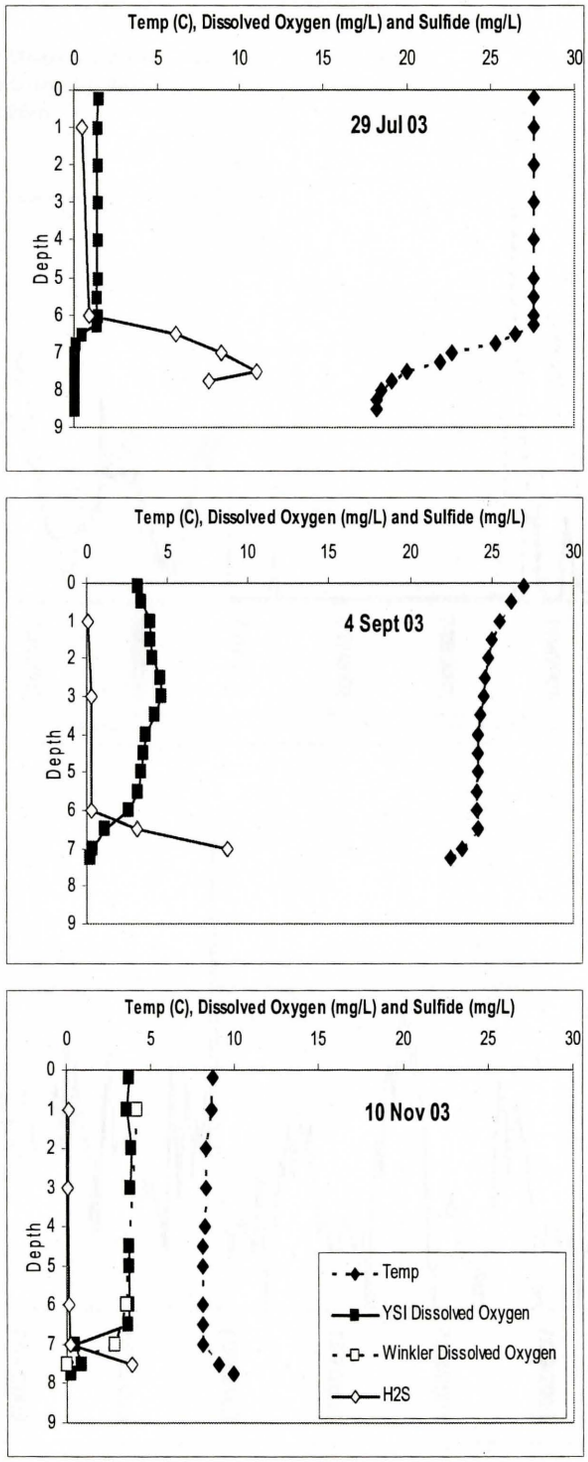


Figure 7: H_2S (total $S^=$), temperature, corrected YSI dissolved oxygen, and where available, Winkler dissolved oxygen profiles collected at the Gilbert Bay station (1018 Buoy).

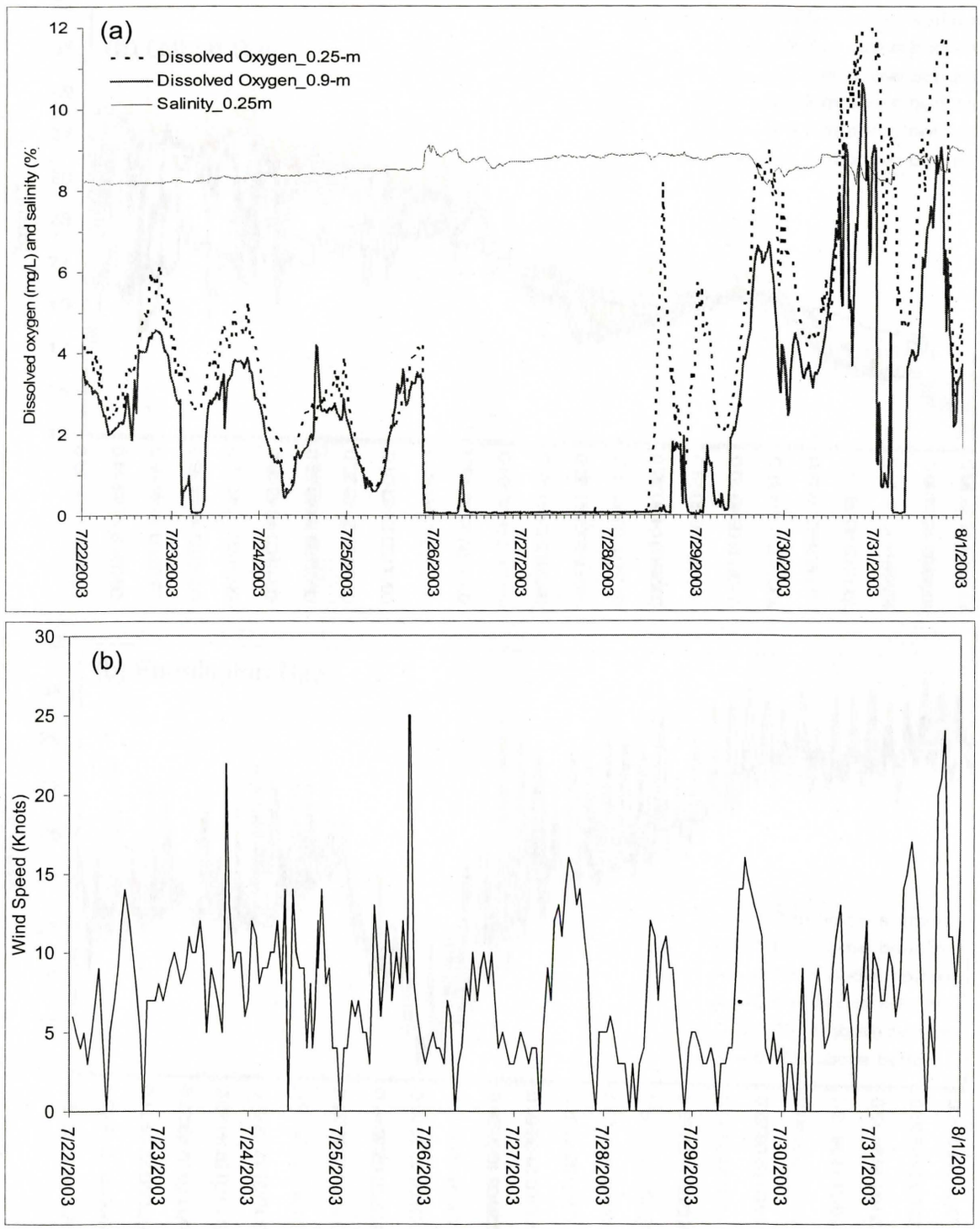
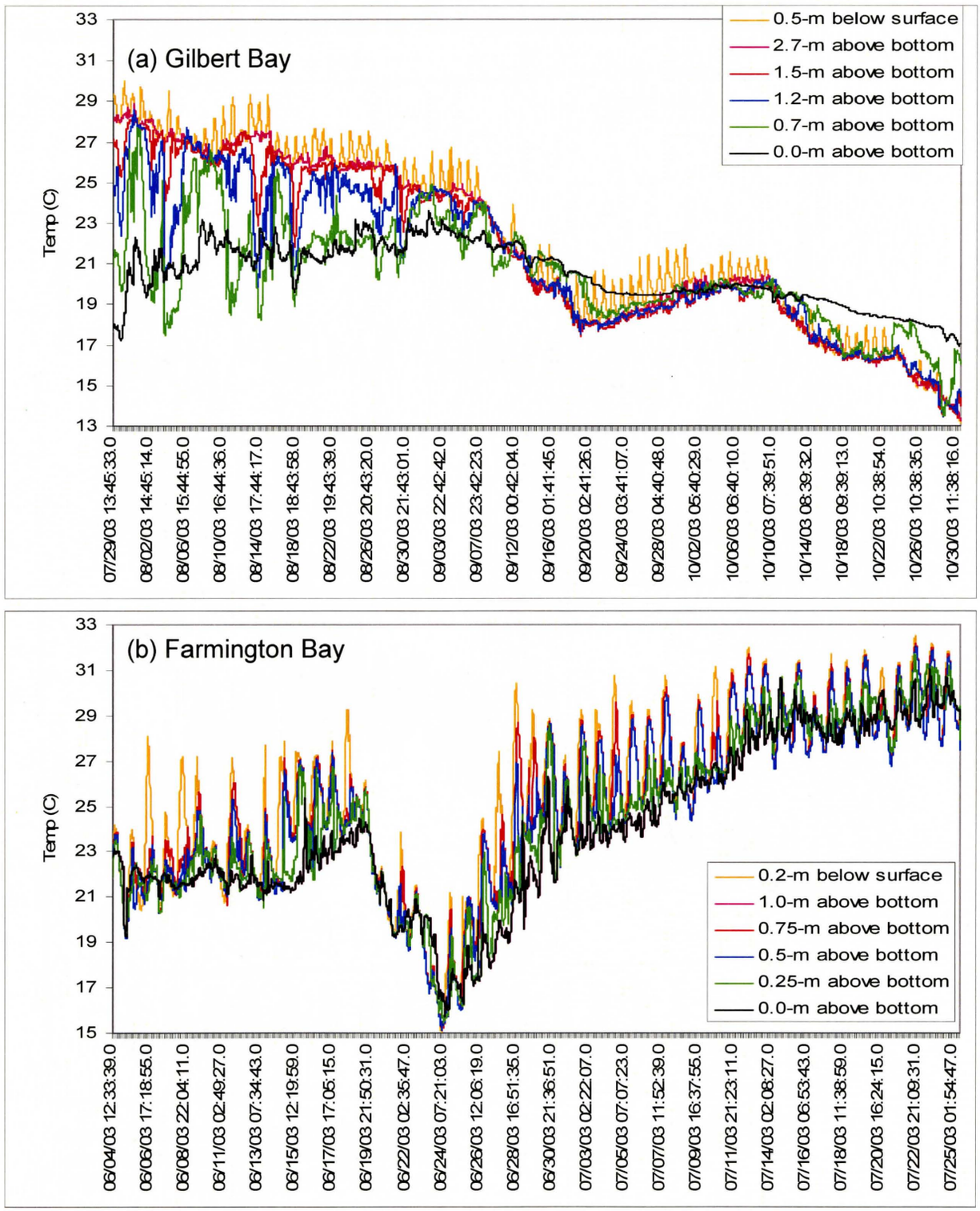


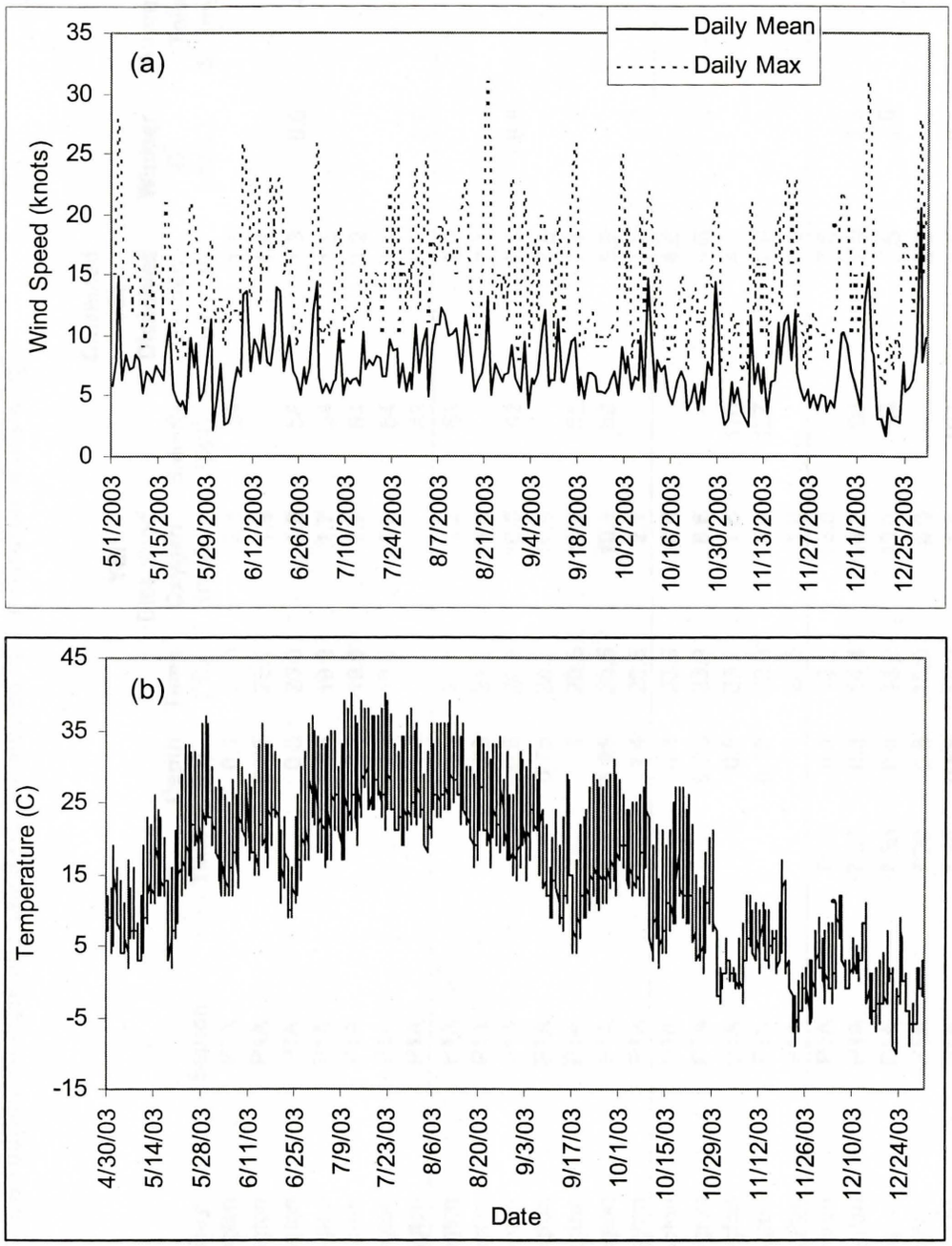
Figure 8: (a) Oxygen and salinity concentrations collected using an oxygen logger near station P1A in Farmington Bay. Note the large day-to-night swings in dissolved oxygen, and the sudden oxygen drop to zero late on 25 July that lasted to mid 28-July. The oxygen drop was coincident with an increase in salinity in the surface water (0.25 m) (b) Wind speed at nearby Salt Lake City International Airport. Notice high spike in wind nearly coincident with oxygen drop in (a).

Appendix I: Complete temperature logger records for Farmington and Gilbert bays.



Appendix I: Temperature logger measurements in (a) Gilbert Bay and (b) Farmington Bay. When the lines approach each other, it indicates that they are the same temperature and mixing is possible. Note the different dates of measurement (29 July to 30 Oct for Gilbert Bay; 4 June to 25 July for Farmington Bay).

Appendix II: Complete weather data for the duration of hydrogen sulfide examination.



Appendix II: (a) Wind speed data and (b) temperature and collected at Salt Lake City International Airport for the period of study. Data was obtained from MesoWest (http://www.met.utah.edu/mesowest/).

Appendix III: All hydrogen sulfide, oxygen, and salinity data collected for the duration of this study.

Date	Lake Bay	Station	Time	Depth (m)	Temp (°C)	YSI Dissolved Oxygen (mg/L)	Salinity (ppt)	Corrected YSI Dissolved Oxygen (mg/L)	Winkler O^2 (mg/L)	Average Total S^{2-} (mg/L)
15-May-03	Farmington	P1A		0.1	20.0	2.1	54	1.5		
15-May-03	Farmington	P1A		0.25	20.1	1.9		1.4		
15-May-03	Farmington	P1A		0.5	20.0	1.8	54	1.3	0.9	-0.63
15-May-03	Farmington	P1A		0.75	19.9	1.7	54	1.2		
15-May-03	Farmington	P1A		1	19.9	1.7	54	1.2		
15-May-03	Farmington	P1A		1.25	19.8	1.5	54	1.1		
15-May-03	Farmington	P1A		1.4			88		0.0	1.00
6-Jun-03	Farmington	P1A		0.1	21.5	11.2	61	7.9		
6-Jun-03	Farmington	P1A		0.25	21.3	11.0		7.7		
6-Jun-03	Farmington	P1A		0.5	20.6	10.8	62	7.5	6.8	0.53
6-Jun-03	Farmington	P1A		0.75	20.5	10.9		7.6		
6-Jun-03	Farmington	P1A		1	20.5	10.9	65	7.4		
6-Jun-03	Farmington	P1A		1.25	20.5	10.1	92	5.9		
6-Jun-03	Farmington	P1A		1.4	20.8	2.1		1.2	0.0	5.91
28-Aug-03	Farmington	P1A		0.1	23.9	8.6		4.6		
28-Aug-03	Farmington	P1A		0.25	23.9	8.6		4.6		
28-Aug-03	Farmington	P1A		0.5	23.7	7.6	110	4.0		0.37
28-Aug-03	Farmington	P1A		0.75	23.3	5.4	127	2.6		
28-Aug-03	Farmington	P1A		1	23.5	1.0		0.5		3.93
23-Oct-03	Farmington	P1A	7:30	0.1	14.2	13.5		7.5		
23-Oct-03	Farmington	P1A	7:30	0.2	14.4	14.2	96	7.9	7.4	0.32
23-Oct-03	Farmington	P1A	7:30	0.4	15.3	13.8	99	7.5	4.9	0.27
23-Oct-03	Farmington	P1A	7:30	0.5	15.3	4.0		2.2		
23-Oct-03	Farmington	P1A	7:30	0.65	15.2	1.4	103	0.7	0.0	1.64
23-Oct-03	Farmington	P1A	11:00	0.2	14.9	17.1	97	9.4	10.5	0.21
23-Oct-03	Farmington	P1A	11:00	0.4	14.9	17.5	96	9.7	10.4	0.17
23-Oct-03	Farmington	P1A	11:00	0.5	14.8	17.6		9.8		
23-Oct-03	Farmington	P1A	11:00	0.6	14.5	16.0		8.9		

23-Oct-03	Farmington	P1A	11:00	0.7	14.7	15.7	99	8.5	6.8	0.26
23-Oct-03	Farmington	P1A	11:00	0.8	15.4	3.2		1.8		
12-Dec-03	Farmington	H2S		0.1	2.0	10.8	34	8.6		0.29
12-Dec-03	Farmington	H2S		0.25	2.0	10.6		8.4		
12-Dec-03	Farmington	H2S		0.5	2.0	10.2	34	8.1		0.43
12-Dec-03	Farmington	H2S		0.75	2.8	10.1	35	8.0		0.3
12-Dec-03	Farmington	H2S		1	3.3	6.8	36	5.3		0.51
12-Dec-03	Farmington	H2S		1.25	3.6	0.8		0.6		
12-Dec-03	Farmington	H2S		1.45	4.7	0.1	59	0.1		8.38
29-Jul-03	Gilbert	1018 Thermistor Buoy		0.2	27.6	3.3	150	1.4		
29-Jul-03	Gilbert	1018 Thermistor Buoy		1	27.6	3.3		1.4		0.48
29-Jul-03	Gilbert	1018 Thermistor Buoy		2	27.6	3.2		1.4		
29-Jul-03	Gilbert	1018 Thermistor Buoy		3	27.6	3.2		1.4		
29-Jul-03	Gilbert	1018 Thermistor Buoy		4	27.6	3.2		1.4		
29-Jul-03	Gilbert	1018 Thermistor Buoy		5	27.6	3.2		1.4		
29-Jul-03	Gilbert	1018 Thermistor Buoy		5.5	27.6	3.0		1.3		
29-Jul-03	Gilbert	1018 Thermistor Buoy		6	27.6	3.2		1.4		0.87
29-Jul-03	Gilbert	1018 Thermistor Buoy		6.25	27.6	3.1		1.3		
29-Jul-03	Gilbert	1018 Thermistor Buoy		6.5	26.5	1.0		0.4		6.15
29-Jul-03	Gilbert	1018 Thermistor Buoy		6.75	25.3	0.1		0.0		
29-Jul-03	Gilbert	1018 Thermistor Buoy		7	22.7	0.1		0.0		8.88
29-Jul-03	Gilbert	1018 Thermistor Buoy		7.25	22.0	0.1		0.0		
29-Jul-03	Gilbert	1018 Thermistor Buoy		7.5	20.0	0.0		0.0		11.04
29-Jul-03	Gilbert	1018 Thermistor Buoy		7.75	19.1	0.1		0.0		8.10
29-Jul-03	Gilbert	1018 Thermistor Buoy		8	18.5	0.1		0.0		
29-Jul-03	Gilbert	1018 Thermistor Buoy		8.25	18.2	-0.1		0.0		
29-Jul-03	Gilbert	1018 Thermistor Buoy		8.5	18.2	-0.1		0.0		
4-Sep-03	Gilbert	1018 Thermistor Buoy		0.1	27.0	7.3	150	3.2		
4-Sep-03	Gilbert	1018 Thermistor Buoy		0.5	26.2	7.9		3.4		
4-Sep-03	Gilbert	1018 Thermistor Buoy		1	25.5	9.2		3.9		0.06
4-Sep-03	Gilbert	1018 Thermistor Buoy		1.5	25.0	9.2		3.9		
4-Sep-03	Gilbert	1018 Thermistor Buoy		2	24.8	9.6		4.1		
4-Sep-03	Gilbert	1018 Thermistor Buoy		2.5	24.6	10.8		4.6		
4-Sep-03	Gilbert	1018 Thermistor Buoy		3	24.5	11.0		4.7		0.31
4-Sep-03	Gilbert	1018 Thermistor Buoy		3.5	24.3	9.9		4.2		

4-Sep-03	Gilbert	1018 Thermistor Buoy	4	24.2	8.6		3.7		
4-Sep-03	Gilbert	1018 Thermistor Buoy	4.5	24.2	8.3		3.5		
4-Sep-03	Gilbert	1018 Thermistor Buoy	5	24.2	7.9		3.4		
4-Sep-03	Gilbert	1018 Thermistor Buoy	5.5	24.1	7.5		3.2		
4-Sep-03	Gilbert	1018 Thermistor Buoy	6	24.1	6.2		2.6		0.25
4-Sep-03	Gilbert	1018 Thermistor Buoy	6.5	24.2	2.7		1.1		3.11
4-Sep-03	Gilbert	1018 Thermistor Buoy	7	23.2	0.8		0.3		8.73
4-Sep-03	Gilbert	1018 Thermistor Buoy	7.25	22.5	0.5		0.2		
10-Nov-03	Gilbert	1018 Thermistor Buoy	0.2	8.7	10.7		3.7		
10-Nov-03	Gilbert	1018 Thermistor Buoy	1	8.6	10.4	164	3.6	4.2	0.16
10-Nov-03	Gilbert	1018 Thermistor Buoy	2	8.3	11.1		3.8		
10-Nov-03	Gilbert	1018 Thermistor Buoy	3	8.3	11.0	164	3.8		0.04
10-Nov-03	Gilbert	1018 Thermistor Buoy	4	8.2					
10-Nov-03	Gilbert	1018 Thermistor Buoy	4.5	8.1	10.8		3.7		
10-Nov-03	Gilbert	1018 Thermistor Buoy	5	8.1	10.7		3.7		
10-Nov-03	Gilbert	1018 Thermistor Buoy	6	8.1	10.7	163	3.7	3.5	0.16
10-Nov-03	Gilbert	1018 Thermistor Buoy	6.5	8.1	10.6		3.7		
10-Nov-03	Gilbert	1018 Thermistor Buoy	7	8.1	1.4	163	0.5	2.8	0.19
10-Nov-03	Gilbert	1018 Thermistor Buoy	7.5	9.0	3.0	186	0.9	0.0	3.88
10-Nov-03	Gilbert	1018 Thermistor Buoy	7.75	9.9	0.9		0.3		